Paris 5/'07

"This Year a New Era Has Commenced & You Can Say You Have Been Present" -- Goethe, the Cannonade of Valmy and Charm Dynamics

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Cannonade of Valmy: 1792 battle in Northern France that saved `New' France from having the Standard Model (of that era) of governance imposed by the `Old' powers.

Tactically a draw, strategically a French victory

Goethe's statement to the Prussian soldiers at camp fire:

'From this place and from this day forth commences a new era in the world's history, and you can all say that you were present at its birth.'

But written up much later; i.e. Goethe -- not unheard of for a theorist -- bragged about a *post*-diction.

in 2007: Strong evidence has surfaced for D oscillations,which could become conclusive by the summer/fall.

A tactical draw in the struggle for gaps in the SM --

x_D & y_D while possibly generated by SM alone,
could contain large contributions from NP --

yet a strategic victory in sight:

CP studies in the future will decide the issue
possibly leading to the dawning of a New Era!

Another & much closer historical analogy:
We had been talking about ~~CP~~ in B decays for years without much resonance - till B oscill. were observed!
(Albeit numerical size much smaller in D decays)

➥ $\Delta C \neq 0$ reclaiming strong Silver Medal f. Super-B

The Menu

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Prologue: New Physics Scenarios & Uniqueness of Charm

➻ New Physics scenarios in general induce FlChNC

✍ their couplings could be substantially stronger for Up-type than for Down-type quarks (unlike in the SM)

(actually happens in some models which `brush the dirt of FlChNC in the down-type sector under rug of the up-type sector)

✍ `think outside the (SM) box': probe FlChNC dynamics of up-type quarks as `hypothesis-generating' research

u $\boxed{c}$ t

only up-type quark allowing full range of probes for New Phys.

basic contention:
charm transitions are a unique portal for obtaining a novel access to flavour dynamics with the experimental situation being a priori favourable (apart from absence of Cabibbo suppression)!

I Inconclusiveness in Interpretation of D^0 Oscillations

(1.1) Basics

☺ fascinating quantum mechanical phenomenon
😐 ambiguous probe for New Physics (=NP)
☺ important ingredient for NP CP asymm. in D^0 decays

$$x_D = \frac{\Delta m_D}{\Gamma_D} \qquad y_D = \frac{\Delta\Gamma_D}{2\Gamma_D}$$

general expectations

- $\Delta\Gamma$: on-shell contributions
  - ➥ ~ insensitive to New Physics
- Δm: virtual intermediate states
  - ➥ sensitive to New Physics

x_D ~$\mathcal{O}$(few %) conceivable in models

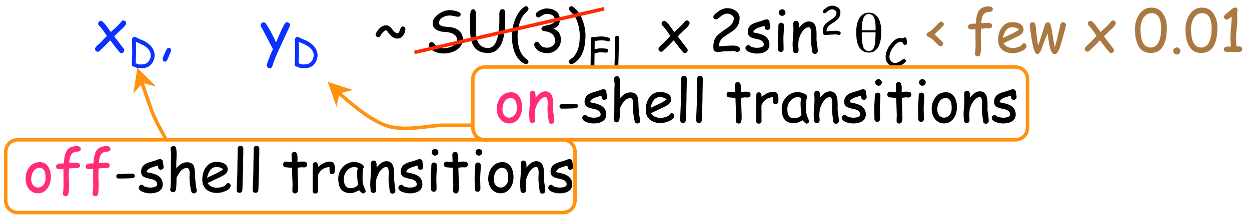
☛ central theoretical issue:

duality at the charm scale?

- ➻ more averaging in x_D than in y_D
- ➥ duality better in x_D than in y_D

D^0-$\overline{D}^0$ oscillations `slow' in the SM

How `slow' is `slow'?



$x_D, \quad y_D \sim \cancel{SU(3)}_{Fl} \times 2\sin^2\theta_C <$ few x 0.01

on-shell transitions

off-shell transitions

While the history of predicting x_D, y_D does not fill one of the glory pages of theoret. HEP, we are not completely off the mark either -- see for example:

hep-ph/9712475 (Lecture notes from 1997):
`CP Violation -- an Essential Mystery in Nature's Grand Design'
p.57f:"*It is often stated that the SM predicts …* $x_D, y_D \leq 3 \times 10^{-4}$ *I myself am somewhat flabbergasted by the boldness of such predictions… I cannot see how anyone can make such a claim with the required confidence…[my estimate]* $x_D, y_D|_{SM} \leq 10^{-2}$."

2 general comments:

(A) $x_D \ll y_D$ *not* a natural scenario!

If $D^0 \to f \to \bar{D}^0$ via an *on*-shell final state

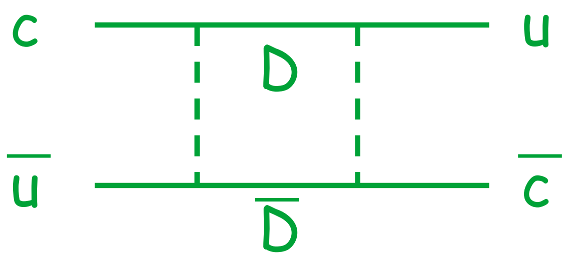
then $D^0 \to$ "f " $\to \bar{D}^0$ via an *off*-shell final state

- dispersion relation connects Δm_D and $\Delta \Gamma_D$

(B)

GIM suppression $(m_s/m_c)^4$ of usual quark box diagram un-typically severe!

- statement oscillations of mesons built from up-type quarks teach us about down-type quark dynamics



2 general comments:

(A) $x_D < y_D$ natural in SM, yet $x_D \ll y_D$ *not*!

If $D^0 \rightarrow f \rightarrow \overline{D}^0$ via an *on*-shell final state

then $D^0 \rightarrow$ "f" $\rightarrow \overline{D}^0$ via an *off*-shell final state

- dispersion relation connects Δm_D and $\Delta\Gamma_D$

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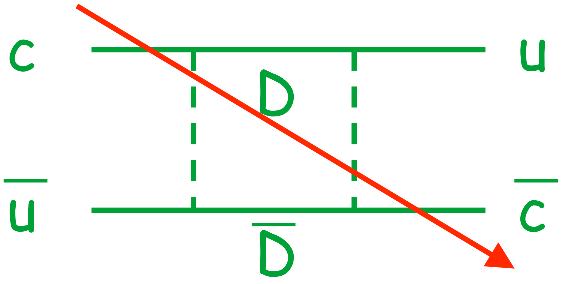

is misleading

(1.2) Numbers

2 complement. approaches to evaluating Δm_D and $\Delta\Gamma_D$ in the SM:

- \`inclusive':

OPE in powers of $1/m_c$, m_s, μ_{had} (quark condensates)

Uraltsev,IB,Nucl.Phys.B592('01)

$m_s^2 m_{had}^4/m_c^{6}$ (vs. m_s^4/m_c^{4})

power counting in $1/m_c$ can be quite iffy

- ❑ x_D (SM)$|_{OPE}$, y_D (SM)$|_{OPE}$ ~ $\mathcal{O}(10^{-3})$ [x_D (SM) < y_D (SM)]
- ❑ unlikely uncertainties can be reduced

- 'exclusive': estimate $SU(3)_{Fl}$ breaking from phase space for 2-, 3-, 4-body modes

A. Falk et al., Phys. Rev. D65 (\`02)

$$y_D\,(SM) \sim 0.01 \xrightarrow[\text{dispersion relation}]{} 0.001 \le |x_D\,(SM)| \le 0.01$$

My conclusion: x_D , $y_D \leq 0.01$

- ✍ could be due `merely' to SM dynamics --
  - ➻ even then it would be a great discovery &
  - ➻ it should be measured accurately --
    - ☞ must know
      (i) whether $(x_D, y_D) \neq 0$ & (ii) x_D=? vs. y_D = ?
      irrespective of theory -- like for ϵ'/ϵ_K!
- ✍ yet might also contain large contributions from NP!

How to resolve this conundrum?

- ❍ theoretical breakthrough?
- ❍ CP violation!

II $\not{C}P$ with & without D^0 Oscillations

- ☺ baryon # of Universe implies/requires NP in $\not{C}\not{P}$ dynamics
- ☺ existence of three-level Cabibbo hierarchy

SM rate CF : CS : DCS ~ 1 : 1/20 : 1/400

- ☺ within SM:
  - ☞ tiny weak phase in 1x Cabibbo supp. modes: $V(cs) = 1 \ldots + i\lambda^4$
  - ☞ no weak phase in Cab. favoured & 2 x Cab. supp. modes (except for $D^\pm \to K_S h^\pm$)
- ☺ CP asymmetry linear in NP amplitude
- ☺ D^0 oscillations at an observable rate! ⟸
- ☺ final state interactions large
- ☺ BR's for CP eigenstates large
- ☺ flavour tagging by $D^{\pm *} \to D\pi^\pm$
- ☺ many $H_c \to \geq 3$ P, VV… with sizeable BR's
  - ➥ CP observables also in final state distributions

(2.1) $\cancel{C}P$ without D^0 Oscillations

direct $\cancel{C}P$

(2.1.1) *time integrated partial widths*

final state interact.
- 😐 necessary evil
- ☺ cannot fake signal
- ☺ ~ large in charm

☺ Cabibbo favour. (CF) modes: need New Physics (except *)

☺ 2x Cabibbo supp. modes (DCS):need New Physics (except *)

exception *: $D^\pm \to K_{S[L]}\,\pi^\pm$

interference between $D^+ \underset{CF}{\longrightarrow} \bar{K}^0\pi^+$ and $D^+ \underset{DCS}{\longrightarrow} K^0\pi^+$

in KM only effect from $\cancel{C}P$ in K^0 - $\bar{K}^0$: $A_S=[+]_S-[-]_S= -3.3 \times 10^{-3}$

exists model by G. D'Ambrosio ('01), which creates observable effect in $D^\pm \to K_{S[L]}\,\pi^\pm$ while not affecting oscillations.

😐 1x Cabibbo supp. modes (SCS)

possible with KM -- benchmark: $\mathcal{O}(\lambda^4) \sim \mathcal{O}(10^{-3})$

New Physics models: $\mathcal{O}(\%)$ conceivable

useful & detailed: Grossman, Kagan, Nir hep-ph/0609178

if observe direct $\cancel{CP} \sim 1\%$ in SCS decays --

- ❑ Is it New Physics for sure?
- ❑ Size of weak phase (and chirality) of its effective operator?

must analyze host of channels in an exercise in theor. engineering

$$\cancel{CP} \sim \underbrace{\sin\Delta\phi_{weak}}_{\text{known from CKM}} \times \underbrace{\sin\Delta\alpha_{strong} \times M_1 \times M_2}_{\text{shaped by strong forces}}$$

- ○ choose set of reduced ME -- involves judgment of decay top.
- ○ fit to comprehensive data on D → PP, PV, VV
- ○ quality control provided by over-redundancy in fit

(2.1.2) Final state distributions: Dalitz plots, T-odd moments

Dalitz plots asymmetries

final state interact. {
- 😐 necessary evil
- ☺ can*not* fake signal

considerable initial overhead -- yet will pay handsome dividends in the long run due to overconstraints

T-odd moments

final state interact. {
- 😐 not necessary
- ☹ a nuissance: can fake signal
- ☺ can be disentangled

---

very promising -- most effective theoretical tools not developed yet for small asymmetries (except Dalitz plot)

Pilot study by Focus (CLEO-c?)

- ☺ \`local' asymmetry likely to be larger than integrated one
- ☺ angular asymmetry can provide info on chirality of underlying effective operator!

An example for a T odd distribution

$K_L \to \pi^+\pi^- e^+e^-$ BR ~ 3×10^{-7}

ϕ = angle between $\pi^+\pi^-$ & e^+e^- planes
forward-backward asymmetry in ϕ: A= 14 % driven by ε=0.002
-- i.e. trade BR for size of asymmetry!

$D \to K \bar{K} \pi^+\pi^-$

ϕ= angle between $\pi^+\pi^-$ & $K \bar{K}$ planes

$$d\Gamma/d\phi\ (D \to K \bar{K} \pi^+\pi^-) = \Gamma_1 \cos^2\phi + \Gamma_2 \sin^2\phi + \Gamma_3 \cos\phi \sin\phi$$

$$d\Gamma/d\phi\ (\bar{D} \to K \bar{K} \pi^+\pi^-) = \bar{\Gamma}_1 \cos^2\phi + \bar{\Gamma}_2 \sin^2\phi + \bar{\Gamma}_3 \cos\phi \sin\phi$$

- Γ_3 drops out after integrating over ϕ
  - Γ_1 vs. $\bar{\Gamma}_1$ & Γ_2 vs. $\bar{\Gamma}_2$: $\cancel{CP}$ in partial widths
- T odd moments $\Gamma_3, \bar{\Gamma}_3 \neq 0$ can be faked by FSI
  yet $\Gamma_3 \neq \bar{\Gamma}_3$ $\Longrightarrow$ $\cancel{CP}$!

(2.2) ~~CP~~ with D^0 Oscillations

All the previously given justifications for CP searches

plus

$L(\Delta C=2) \neq 0$

- provides a much wider stage for ~~CP~~ to surface
- allowing us to decide whether NP is involved.

Analogies with two other cases,
one from the past & one from the present:
K^0 & B_s oscillations

$\Delta S=2$:

Assume -- contrary to history -- that people had accepted the SM with 2 families when $\Delta M_K \neq 0$ was observed & knew about possibility of ~~CP~~.
They would have reasoned that LD dynamics could produce ~ 1/3 of ΔM_K via $K^0 \to$ "π ,η,η',$\pi\pi$, ... " $\to \overline{K^0}$ and
SD dynamics via the quark box diagram the rest.
This might have led to the proposal to search for $K_L \to \pi\pi$ to establish the presence of NP, namely the 3rd family (which is irrelevant for ΔM_K).

$\Delta B=2$ -- the topical example:
The observed value of $\Delta M(B_s)$ is fully consistent with SM expectations -- within sizable uncertainties. Yet a subdominant NP contribution to $\Delta M(B_s)$ could still provide the dominant source of time dependent ~~CP~~ in $B_s \to \psi\phi$!

oscillations can generate time *dependent* CP asymmetries

- ❑ none seen so far down to the 1% (1%/$tg^2\,\theta_C$) level --
- ☞ they are ~ (x_D or y_D) (t/τ_D)sin ϕ_{weak};
  - ➻ with x_D , $y_D \leq 0.01$ a signal would not have been credible
  - ➻ yet now it is getting interesting!

Scenario (A)

LD dynamics (involving barely 2 families) cannot generate ~~CP~~!

I.e., minimal scenario: *no* significant ~~CP~~ in $L(\Delta C=2)$,

direct ~~CP~~ only: (i) $|q|=|p|$,

whereas (ii) $|T(D \rightarrow f)| \neq |T(\overline{D} \rightarrow \overline{f})|$

(iii) $\mathrm{Im}\,(q/p)\overline{\rho}(f) \neq 0$

- CF: $K_S\pi^0$, $K_S\rho^0$, $\boxed{K_S\phi}$ $\mathrm{Im}V(cs)V(ud) = \eta|V(cb)|^2 \sim 0.6\mathrm{x}10^{-3}$

- DCS: $D^0 \rightarrow K^+\pi^-$ -- $\mathrm{Im}V(cd)V(us) = 0$

  yet NP models a la D'Ambrosio

- CS: $D^0 \rightarrow K^+K^-, \pi^+\pi^-$ -- time depend. & indep. CP

Scenario (B)

NP contributes significantly to $L(\Delta C=2)$

➥ expect significant source for $\cancel{CP}$ in $L(\Delta C=2)$,

(i) $|q| \neq |p|$, (ii) $|T(D \rightarrow f)| \neq |T(\overline{D} \rightarrow \overline{f})|$, (iii) Im $(q/p)\overline{\rho}(f) \neq 0$

- CF: $D^0 \rightarrow K_S \phi$ $\quad A_{CP}(t) = (x_D \sin\phi_{NP} - y_D \varepsilon_{NP} \cos\phi_{NP})(t/\tau_D)$
  $L(\Delta C=2) \rightarrow$ ϕ_{NP} & $\varepsilon_{NP} = 1 - |q/p|$
- CS: $D^0 \rightarrow K^+K^-, \pi^+\pi^-$ $\quad A_{CP}(t)=\underline{(}x_D \sin\phi'_{NP} - y_D \varepsilon_{NP} \cos\phi'_{NP})(t/\tau_D)$
  $D^0 \rightarrow K^+K^-\pi^+\pi^-$ $\quad \Gamma_3(t)$, $\Gamma_3(t)$!
- DCS: $D^0 \rightarrow K^+\pi^-$ -- ditto (+NP models a la D'Ambrosio)
- SL: $D^0 \rightarrow l^-X^+$ vs. $\overline{D}^0 \rightarrow l^+X^-$
  $a_{SL} \sim \mathrm{Min}[\Delta\Gamma/\Delta M, \Delta M/\Delta\Gamma] \sin\phi_{NP}$, $\quad (\Delta\Gamma/\Delta M) \sim O(1)$

(2.3) Benchmarks

☞ Allowed New Physics scenarios could produce $\cancel{CP}$ close to present experim. bounds, but hardly higher!

- time dependant CP asymmetries in
  - $D^0 \to K^+K^-, \pi^+\pi^-, K_S\phi$ down to $\mathcal{O}(10^{-4})$
  - $D^0 \to K^+\pi^-$ down to $\mathcal{O}(10^{-3})$

  LHCb: ~ $5\text{x}10^7$ $D^* \to D\pi \to [KK]_D\pi$ in 10^7 sec
- direct $\cancel{CP}$ in partial widths of
  - $D^\pm \to K_{S[L]}\pi^\pm$ down to $\mathcal{O}(10^{-3})$
  - in a host of 1xCS channels down to $\mathcal{O}(10^{-3})$
  - in 2xCS channels down to $\mathcal{O}(10^{-2})$
- direct $\cancel{CP}$ in the final state distributions:

  Dalitz plots, T-odd correlations etc. down to $\mathcal{O}(10^{-3})$

III Conclusions & Outlook

Did not discuss $\cancel{CP}$ through existence of transition:

$e^+e^- \to \bar{D}^0D^0 \to$ 2 CP eigenstates of same parity

Cleo-c & BESIII

[Babar should have candidates for

$e^+e^- \to B_d\bar{B}_d \to$ 2 CP eigenstates of same parity]

- there is a lot of work to be done
  - establish $(x_D,y_D) \neq 0$
  - determine x_D=? vs. y_D = ?
  - go after $\cancel{CP}$

`Nil sine magno labore!'

- there is fame within your grasp!